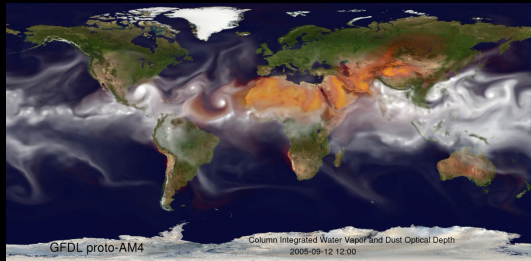


The FV3 dynamical core and the Next Generation Global Prediction System (NGGPS)

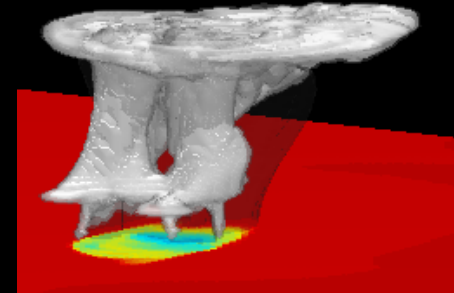


50-km GFDL-AM4

global



Regional



1-km "Super HiRAM"

S.-J. Lin & GFDL FV3 team
NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ

FV3 presentation at COLA
Nov 30, 2016

NWP is in GFDL's DNA

A 1955 document recently found at GFDL:

"Dynamics of the general circulation"

It was stated that

- **"forecasts over 24 hours are possible"**
- **"the effect of mountains and precipitation can be ignored"**

The 1st successful NWP experiment led to the establishment of GFDL, a predominantly climate modeling center

60 years later, a weather-climate model unification (seamless model) is within reach

V. 1/1 1/4 Draft
July 29, 1955

DYNAMICS OF THE GENERAL CIRCULATION

little suggested by the at hand to day with S.W. + J. Charney

1. In 1947, a project was started in Princeton by the U.S. Navy, and U.S. Air Force, for ~~theoretical and~~ *theoretical and* computational investigations in meteorology, with particular regard to ~~the~~ *the* development of methods of numerical weather forecasting. After a few years of experimenting, *concentrated on* the project ~~concentrated on~~ *concentrated on* exploring the validity and the use of the differential equation methods ~~of~~ *developed by* Dr. J. Charney, for numerical forecasting.

For this purpose, the U.S. Army Ordnance Corps ENIAC computing machine *and in 1951* was used in 1950 ~~and~~, and the Institute for Advanced Study's own computing machine from 1952 onward. Subsequently, use was also made of the IBM 701 machine in New York City. With the help of these computing tools, it was found that forecasts over periods like 24 (and up to ~~48~~ *48*) hours are possible, and give significant improvements over the normal, subjective method of forecasting. Certain experiments demonstrated that even phenomena of ~~cyclogenesis~~ *cyclogenesis* could be predicted. A considerable number of sample forecasts were made, which permitted the above mentioned evaluation of the ~~value~~ *validity* of the method. A large number of variants ~~were~~ *eliminating successively* were also explored, particularly with respect to ~~eliminating successively~~ *eliminating successively* the major mathematical approximations that the original method contained. It must be noted, however, that the method, and also all its variants, which exist at the present, are still affected with considerable simplifications of a physical nature. Thus, the effects of radiation have only been taken into consideration in exceptional cases, the same is true for the effects of *geography and* topography, while humidity and precipitation have not been considered at all. *That significant* ~~That significant~~ results could, nevertheless, be ~~obtained~~ *time-* obtained, is due to the relatively short span of the forecasts. Indeed, over 24 or 48 hours ~~of~~ the above mentioned effects do not yet come into play decisively.

The Next Generation Global Prediction System (NGGPS)

*An inter-agency effort to develop a **unified** global model for 0-100 day predictions, to be used for the next 10-20 years*

Non-hydrostatic dynamical core inter-comparisons:

- **GFDL FV3:** Finite-Volume on the cubed-sphere
- **NCAR MPAS:** Finite-difference/finite-volume on icosahedral grid
- ~~NCEP NMM-UJ:~~ finite-difference on cubed-sphere grid
- ~~ESRL NIM:~~ finite-difference/finite-volume on icosahedral grid (similar to FIM)
- ~~NAVY NEPTUNE:~~ spectral-element on cubed-sphere (similar to NCAR CAM-SE)

Phase-1 comparisons:

- idealized tests, 3 km global cloud-permitting simulations, and computational benchmarks

Phase-2 comparisons:

- Computational performance
- Idealized tests
- Effective resolution (judged by Kinetic Energy spectra)
- Real-data forecasts at 13 km with the operational GFS physics and ICs

Timeline on FV3-NGGPS development at GFDL

- **Mar 2016:**
GFDL submitted 74 cases of hindcasts with un-tuned GFS physics to the Dycore Test Group (DTG) for evaluation
- **June 2016:**
DTG briefing to UMAC, recommending selection of FV3 for NGGPS
- **August 2016**
Tuning of GFS physics started at GFDL
- **Oct 2016:**
To improve cloud-scale predictions, GFS cloud microphysics replaced by GFDL 6-category bulk scheme; as it turns out, the global prediction at low-resolution also significantly improved!
- **Nov 2016:**
 - GFDL has built a **FV3-based NGGPS prototype model** (sans a DA system) that produced **significantly better forecasts than operationally GFS** (using interpolated GFS ICs). The same model produced forecasts as good as ECMWF when using atmospheric IC from IFS (with GFS land, time-frozen SST, and other handicaps).

What's "Finite-Volume" about FV3?

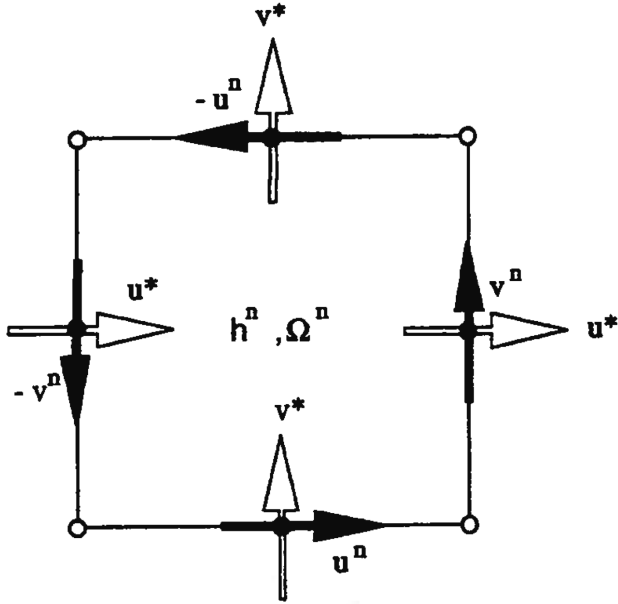
(20-yr of R/D in one slide)

1. Vertically Lagrangian control-volume discretization based on 1st principles (Lin 2004)
 - Conservation laws solved for the control-volume bounded by two Lagrangian surfaces
2. Physically based forward-in-time "horizontal" transport (Lin & Rood 1996)
 - Conservative analog to the non-conservative two-time-level semi-Lagrangian schemes in ECMWF-IFS; locally conservative and monotonic via constraints on sub-grid distributions (Lin & Rood 1996; Putman & Lin 2007)
 - Space-time discretization is non-separable -- hallmark of a physically based FV algorithm
3. Combined use of C & D staggering with optimal FV representation of Potential Vorticity and Helicity (Lin & Rood 1997)
 - important from synoptic-scale down to tornado-scale
4. Finite-volume integration of pressure forces (Lin 1997)
 - Analogous to the forces acting on an aircraft wing (lift & form-drag forces)
 - Horizontal and vertical discretization are non-separable (Arakawa-type linear analyses developed in the 70s are not applicable to FV3's Lagrangian discretization)
5. For non-hydrostatic extension, the vertically Lagrangian discretization reduces the sound-wave solver into a 1-D problem (solved by either an exact Riemann solver or a semi-implicit solver with conservative cubic-spline)



A balanced approach to “horizontal” grid staggering:

The C+D grid (Lin & Rood 1997)



C & D can work together,
like Yin-Yang

Pressure gradient (linear):

- C grid requires no averaging (best)
- D grid requires averaging in both directions (worst); can be drastically improved with 4th order FV scheme

Geostrophic balance (linear):

- C grid requires averaging in both directions (worst)
- D grid requires NO averaging (best)

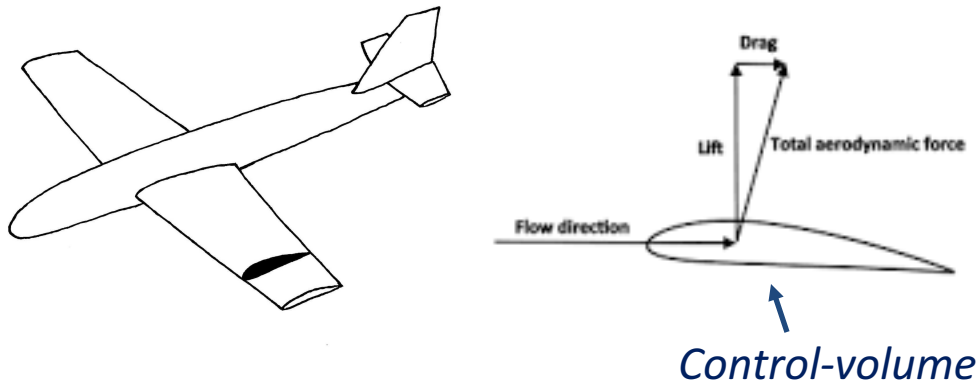
Potential Vorticity & Helicity (nonlinear):

- C grid is the worst grid for vorticity & helicity
- D grid is the best for vorticity advection and the representation of updraft helicity (severe storms)

**A combination of C and D is better than
a pure C or a pure D grid**

Inspired by the aerodynamics

The forces acting on the wing of an aircraft

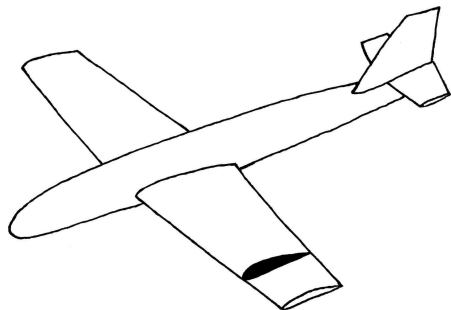


- The “**lift**” force is the net force in the vertical direction
 - **Hydrostatic (cruising, no acceleration)**: the lift balances the weight ($dw/dt = 0$)
 - **Non-hydrostatic (g-force)**: the lift produces the vertical acceleration ($dw/dt = g_force$)
- The form “**drag**” is the projection of the force in the horizontal direction ($du/dt = thrust_force$)



Inspired by the aerodynamics

Hydrostatic model →



$dw/dt = \text{Zero}$

A “Glider” or a “passenger-jet” at cruising altitude

Non-hydrostatic model →



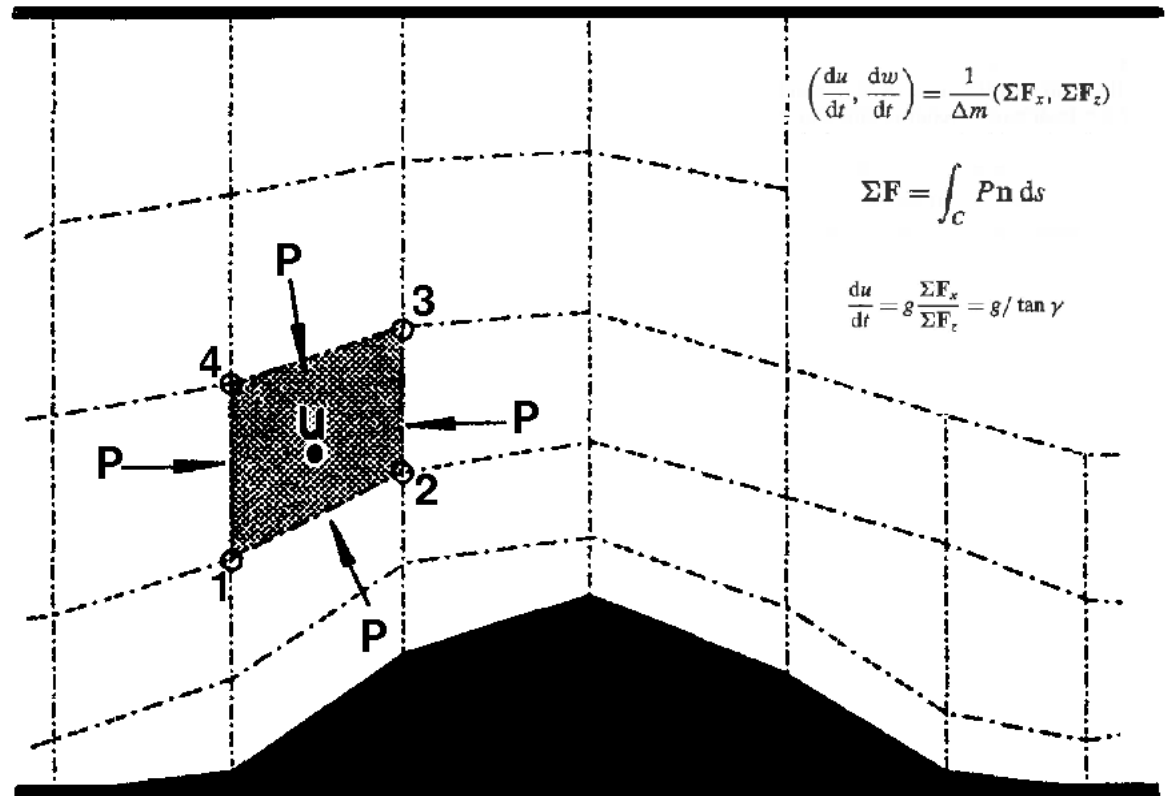
$dw/dt = g_force$

F-22 Raptor

Physically based Finite-Volume integration of Pressure Force

Lin (1997, QJ)

- The model top and bottom are Lagrangian surfaces
- Physically based finite-volume integration using Newton's 2nd law and Green's integral theorem
- Vertical-horizontal discretization is therefore non-separable



$$\left(\frac{du}{dt}, \frac{dw}{dt}\right) = \frac{1}{\Delta m} (\Sigma F_x, \Sigma F_z)$$

$$\Sigma \mathbf{F} = \int_C P \mathbf{n} ds$$

$$\frac{du}{dt} = g \frac{\Sigma F_x}{\Sigma F_z} = g / \tan \gamma$$

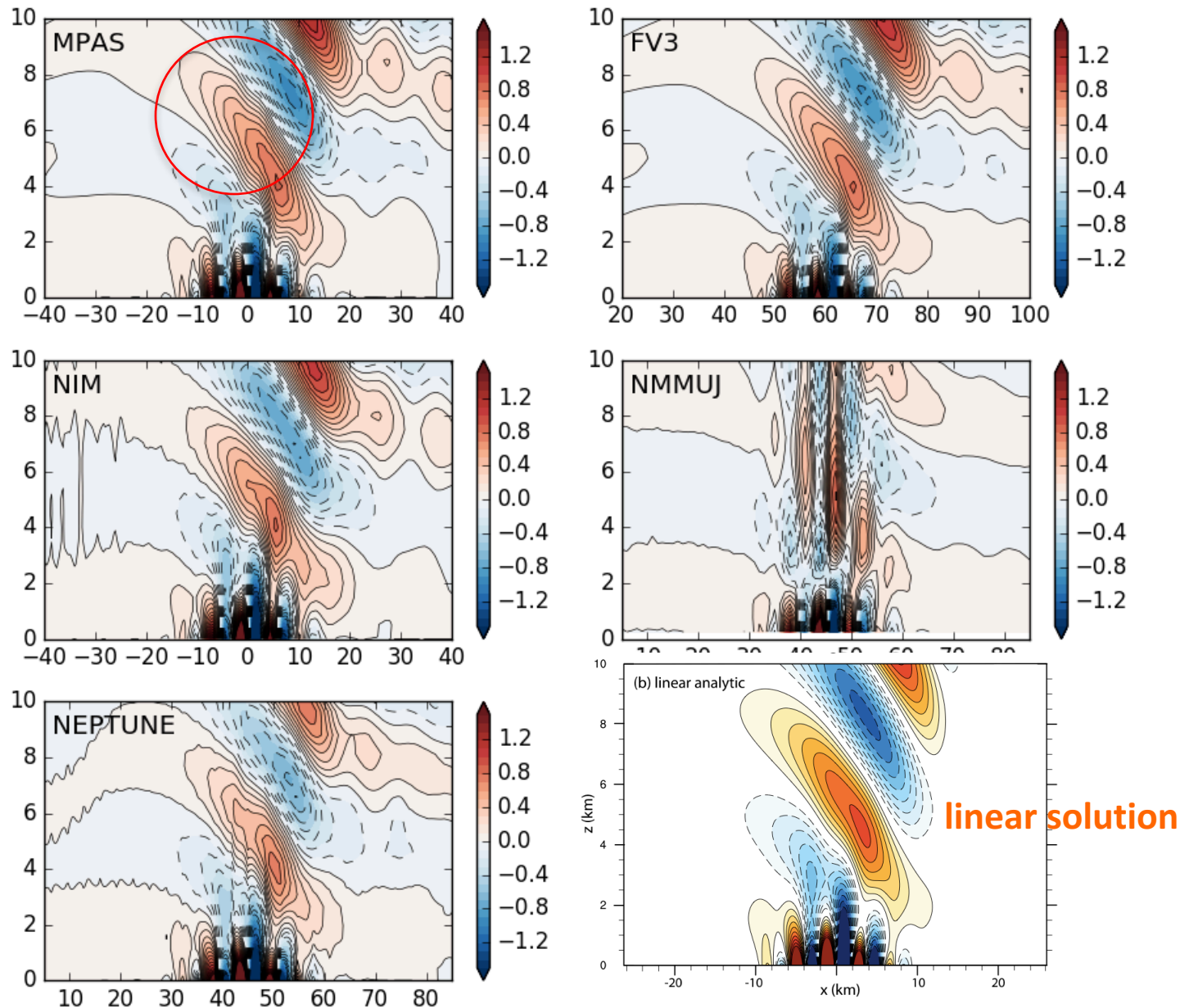
$$\left(\frac{du}{dt}, \frac{dw}{dt}\right) = \frac{1}{\Delta m} (\Sigma F_x, \Sigma F_z)$$

$$\Sigma \mathbf{F} = \int_C P \mathbf{n} ds$$

$$\frac{du}{dt} = g \frac{\Sigma F_x}{\Sigma F_z} = g / \tan \gamma$$

NGGPS phase-1 linear mountain wave test (case: M2) at hour-2

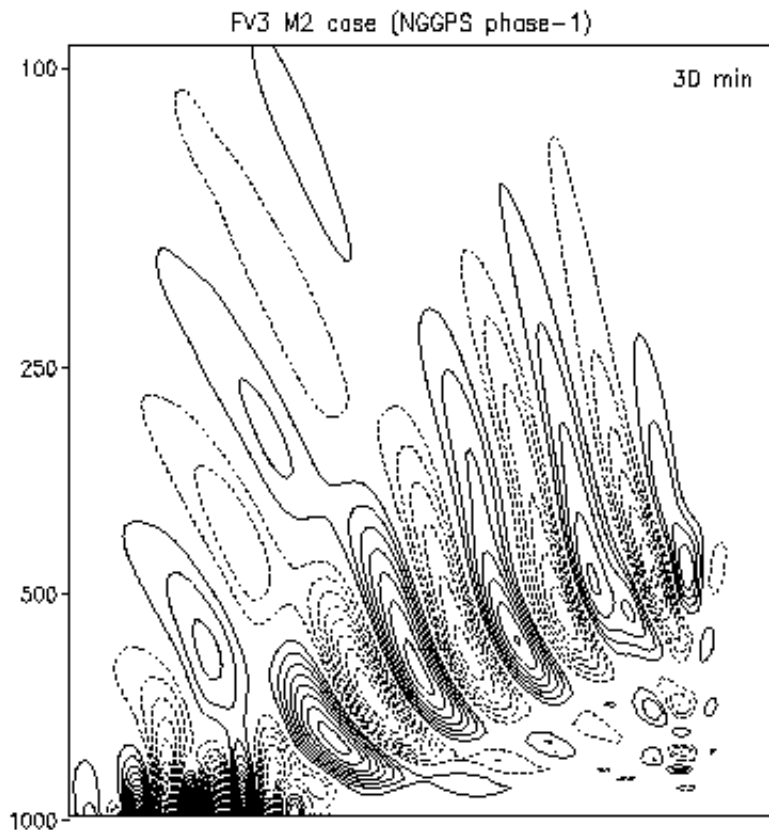
(a constant u-wind blowing from west to east)



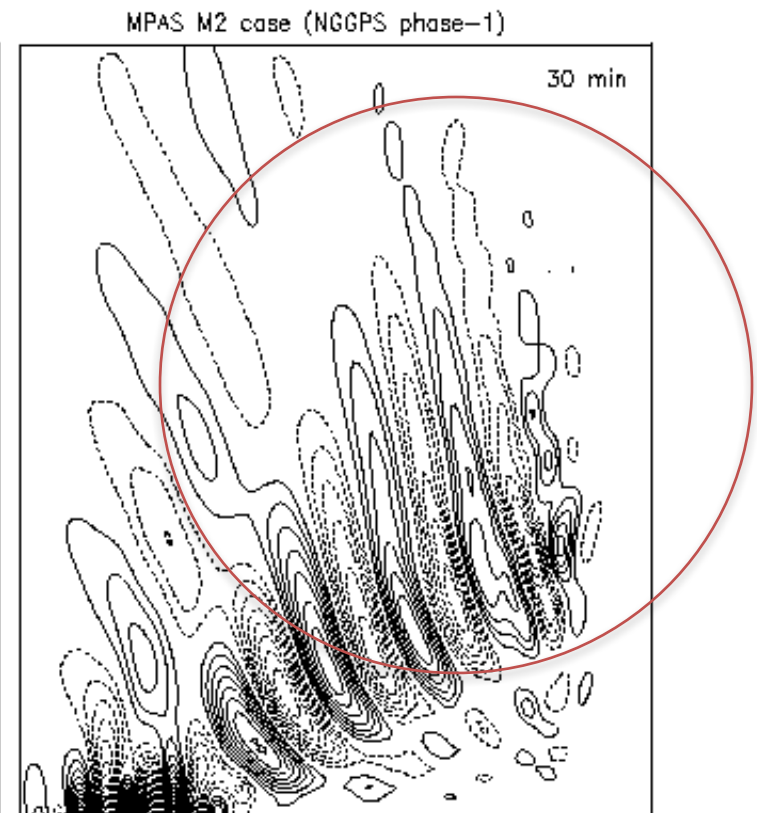
NGGPS phase-1 Mountain wave test at t=30-min

MPAS numerical noises propagate out of mountain region

FV3



MPAS

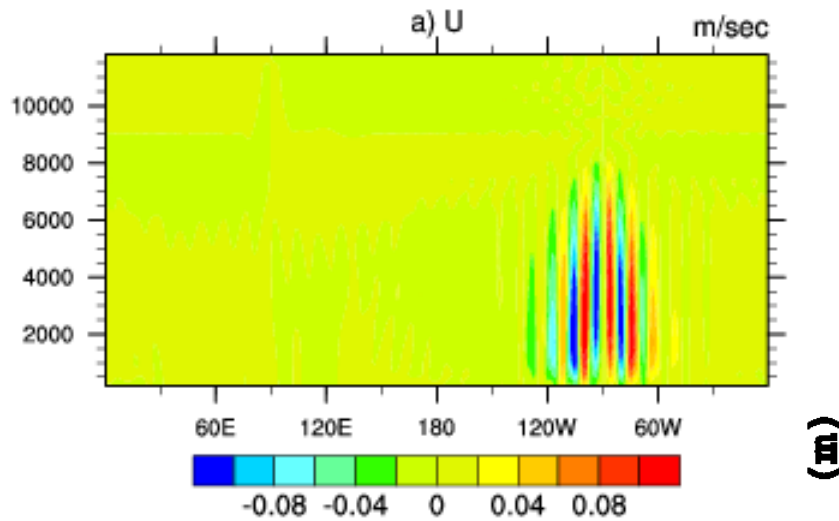


DCMIP-2012 “hydrostatic equilibrium test”

For this “atmosphere-at-rest” test, noises can not propagate out of the source region
(regional-only vs global design)

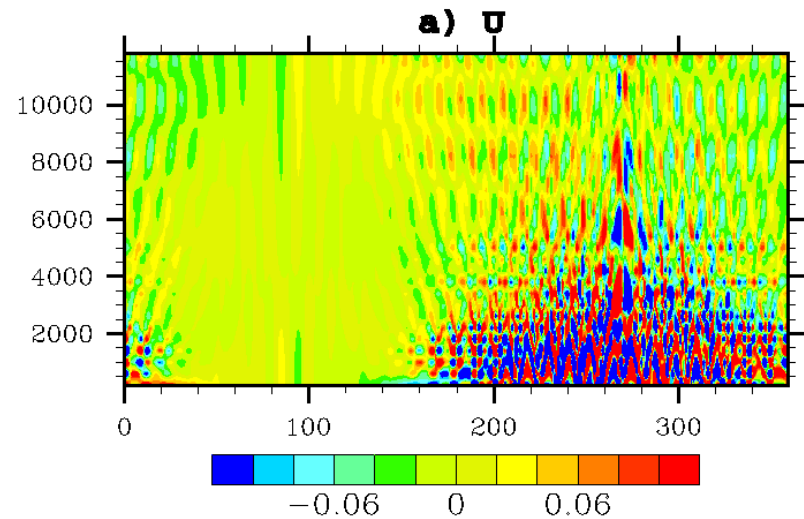
FV3

FV3 - GFDL, Test 200, $t = 6$ days, 30 level



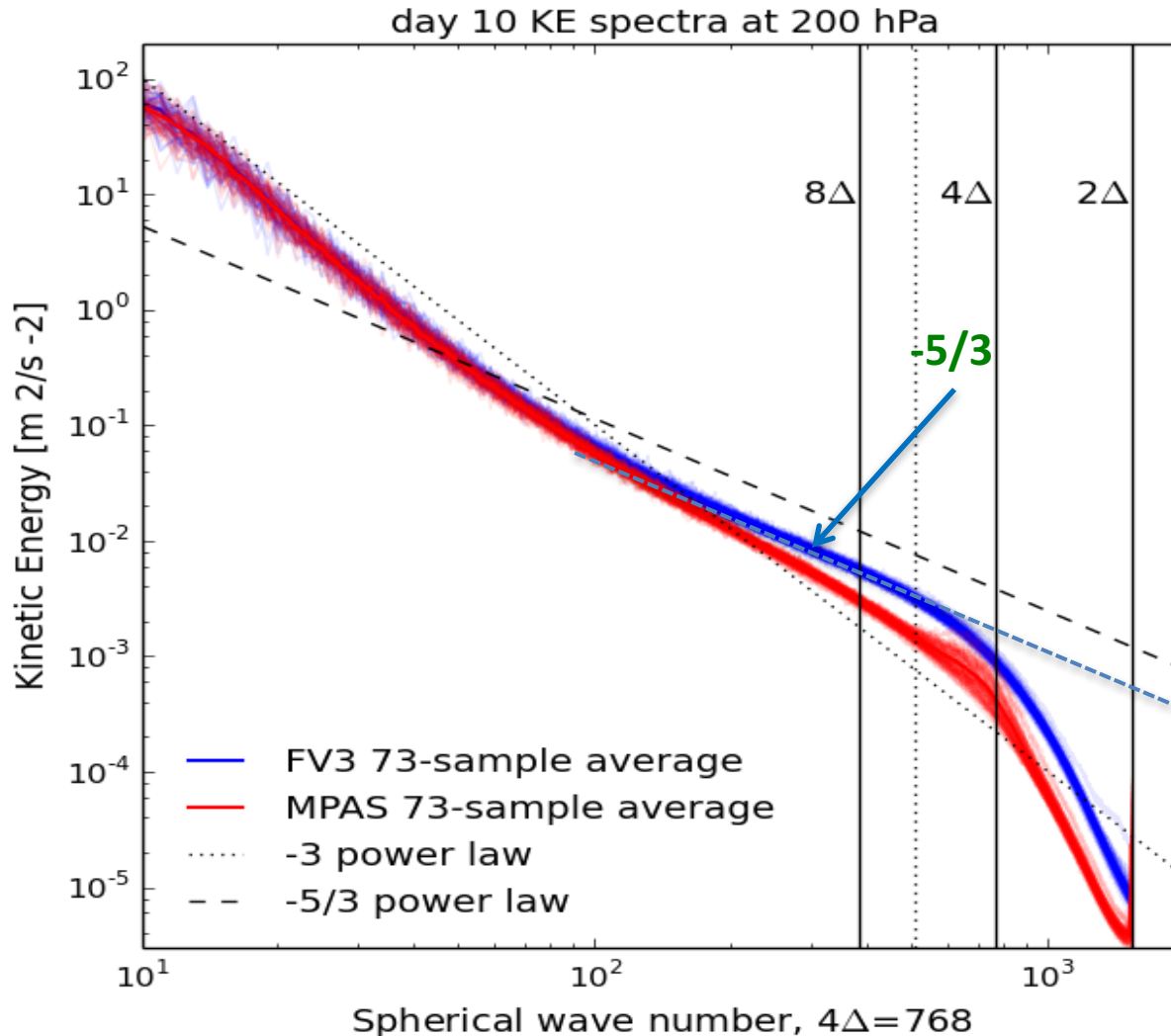
MPAS

MPAS, Test 200, L30, $t = 6$ days



Algorithm design and diffusion tuning: FV3 vs MPAS

The story told by the KE spectra (composite 73 cases, 13-km NGGPS phase-2)



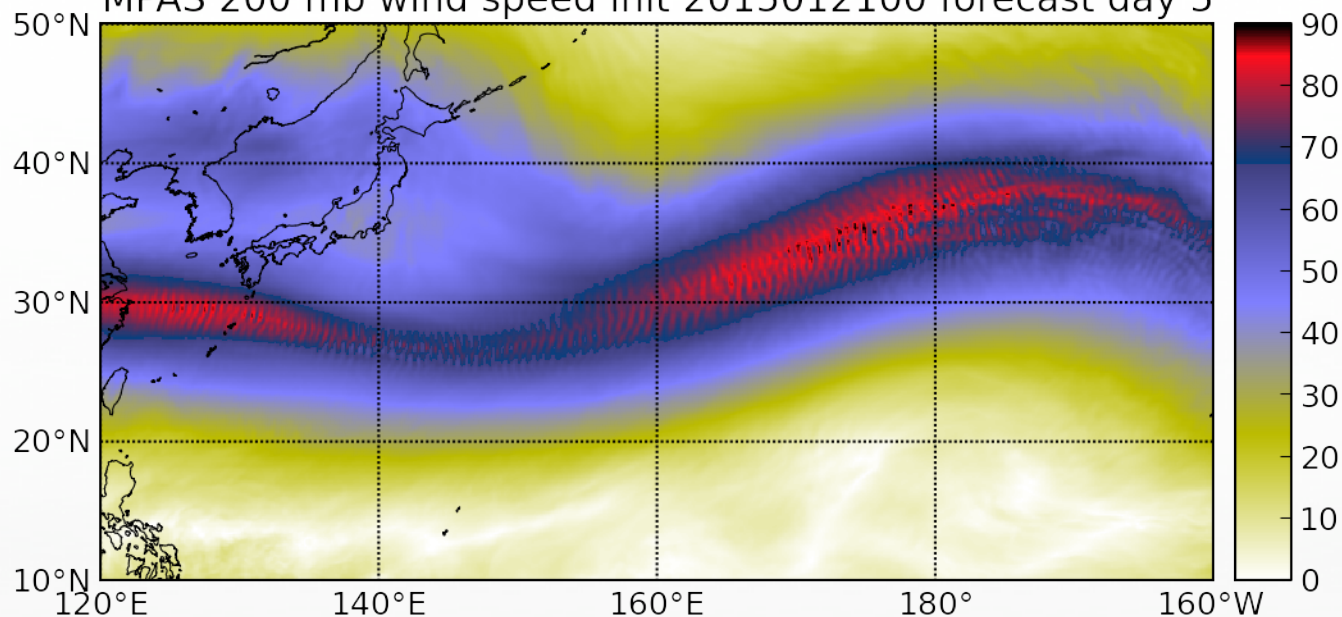
- FV3 simulated the -5/3 “meso-scale” spectrum
- MPAS has an energy deficit of $\sim 50\%$ in the meso-scale and failed to simulate the -5/3 spectrum

The ~ 4 -delta-x noises in MPAS 10-day forecasts

(the source of the false $-5/3$ spectra in MPAS)

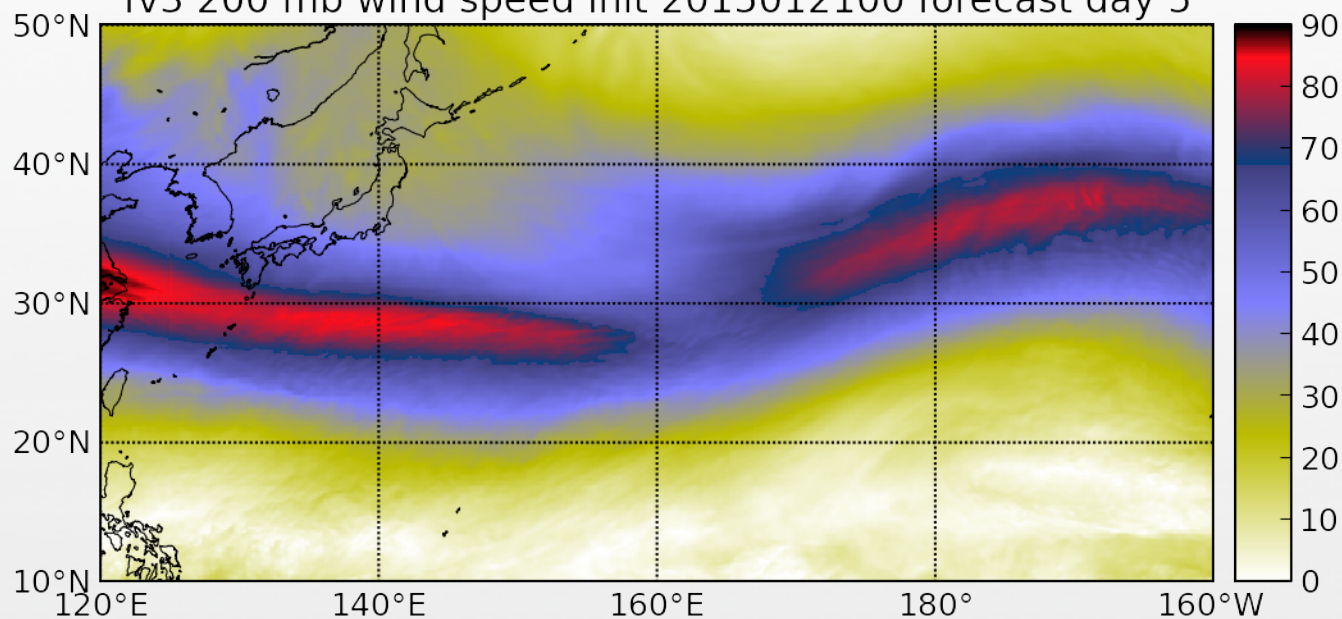
(noises appear in MPAS forecasts whenever the jet stream is strong)

MPAS 200 mb wind speed init 2015012100 forecast day 5



MPAS

fv3 200 mb wind speed init 2015012100 forecast day 5



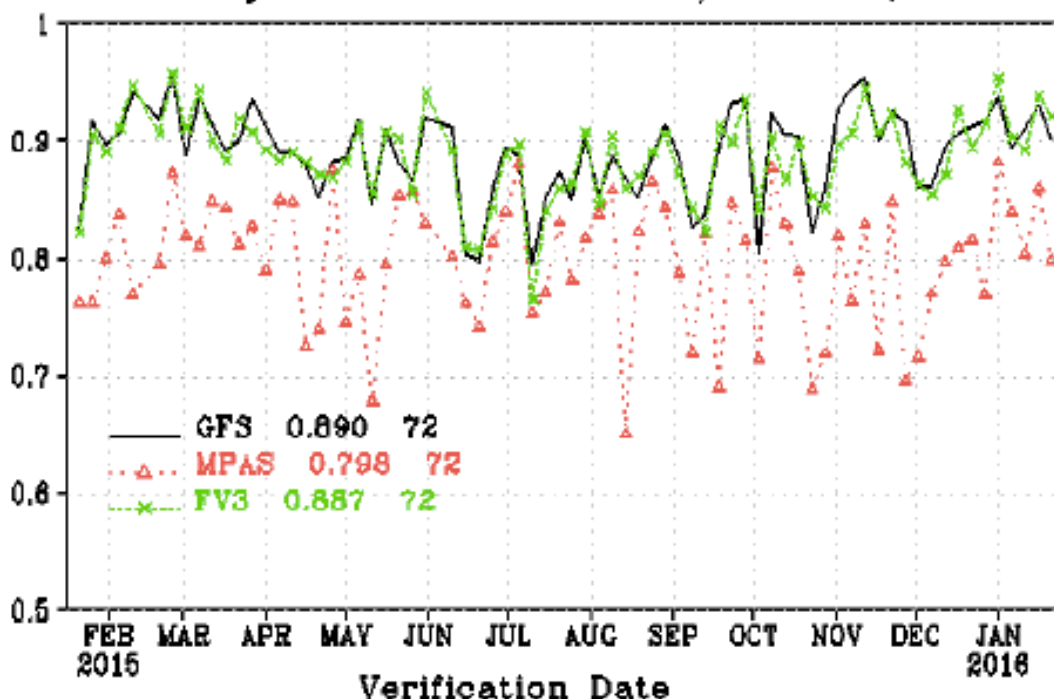
FV3



#3: Retrospective 13 km Forecast Skill

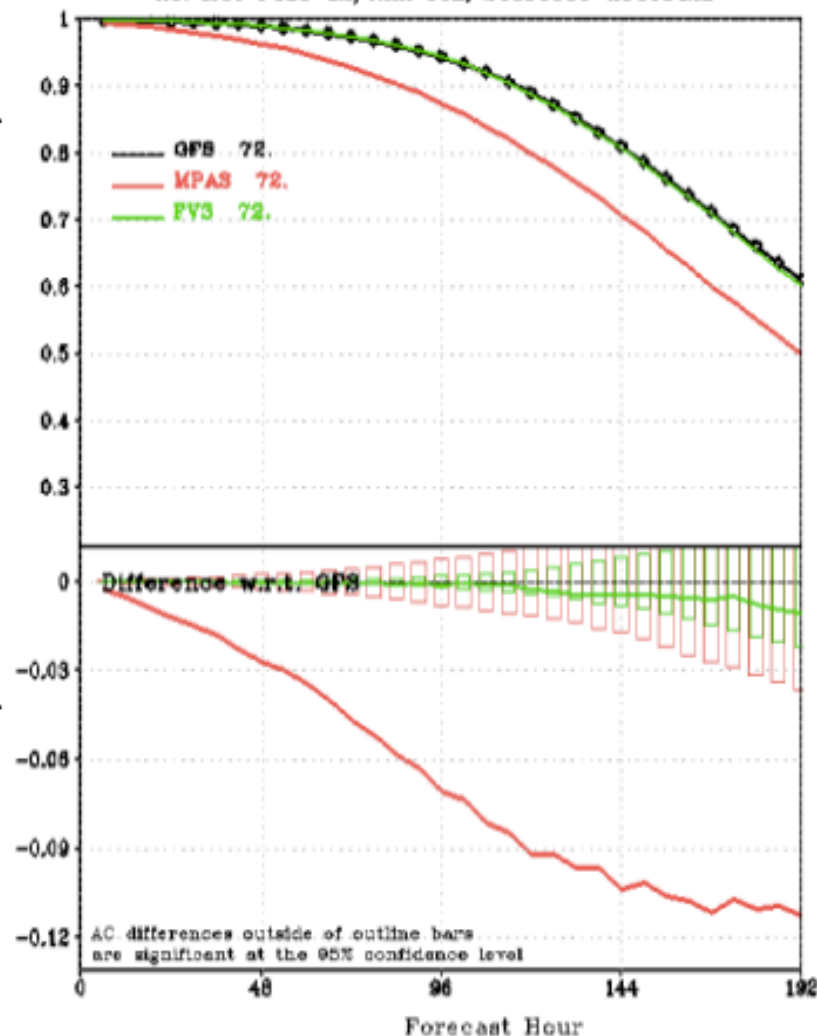


Anomaly Correl: HGT P500 G2/NHX 00Z, fh120



FV3 forecast skill matches the GFS using GFS ICs and GFS Physics

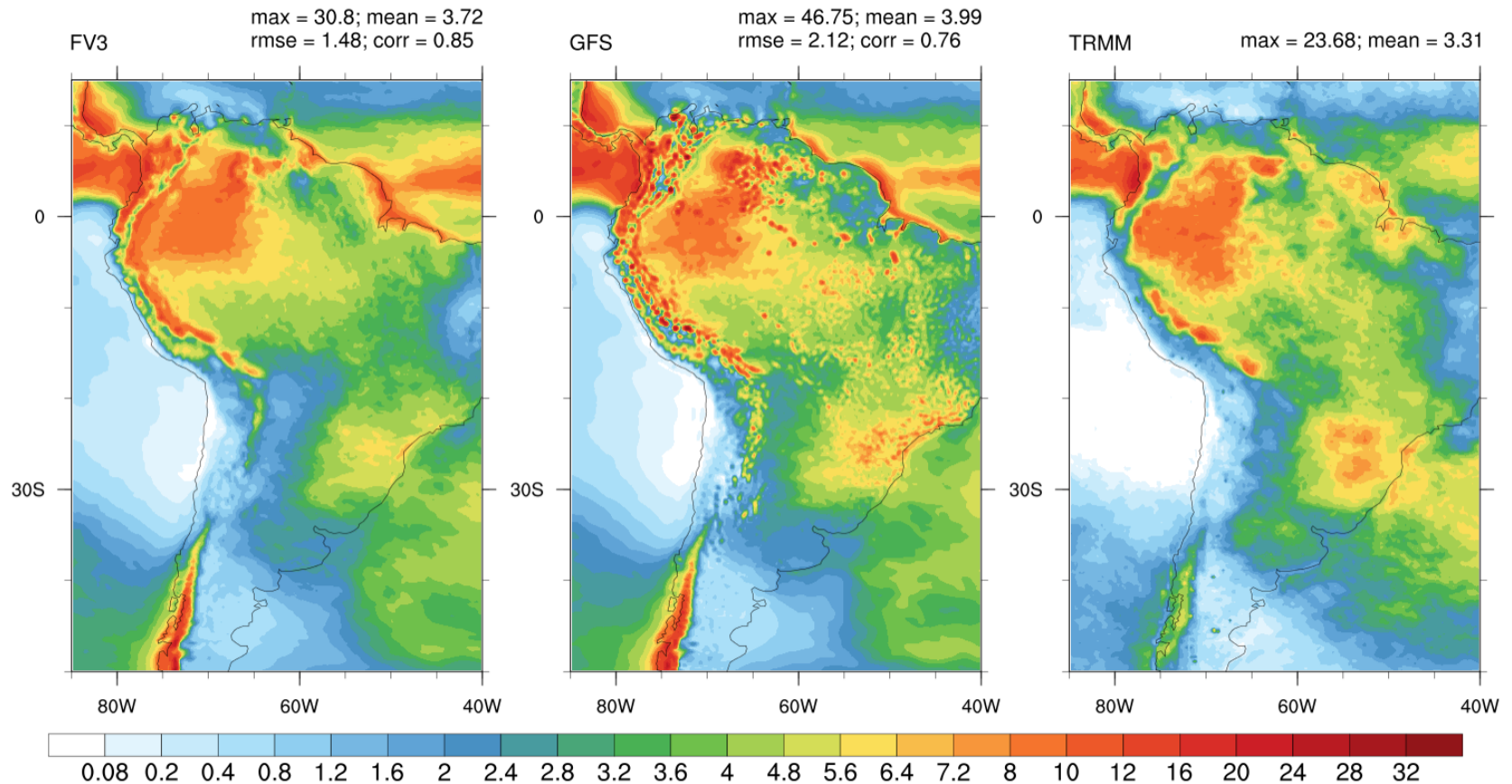
AC: HGT P500 G2/NHX 00Z, 20160116-20160125



Why spectral models are bad at high resolution?

South America

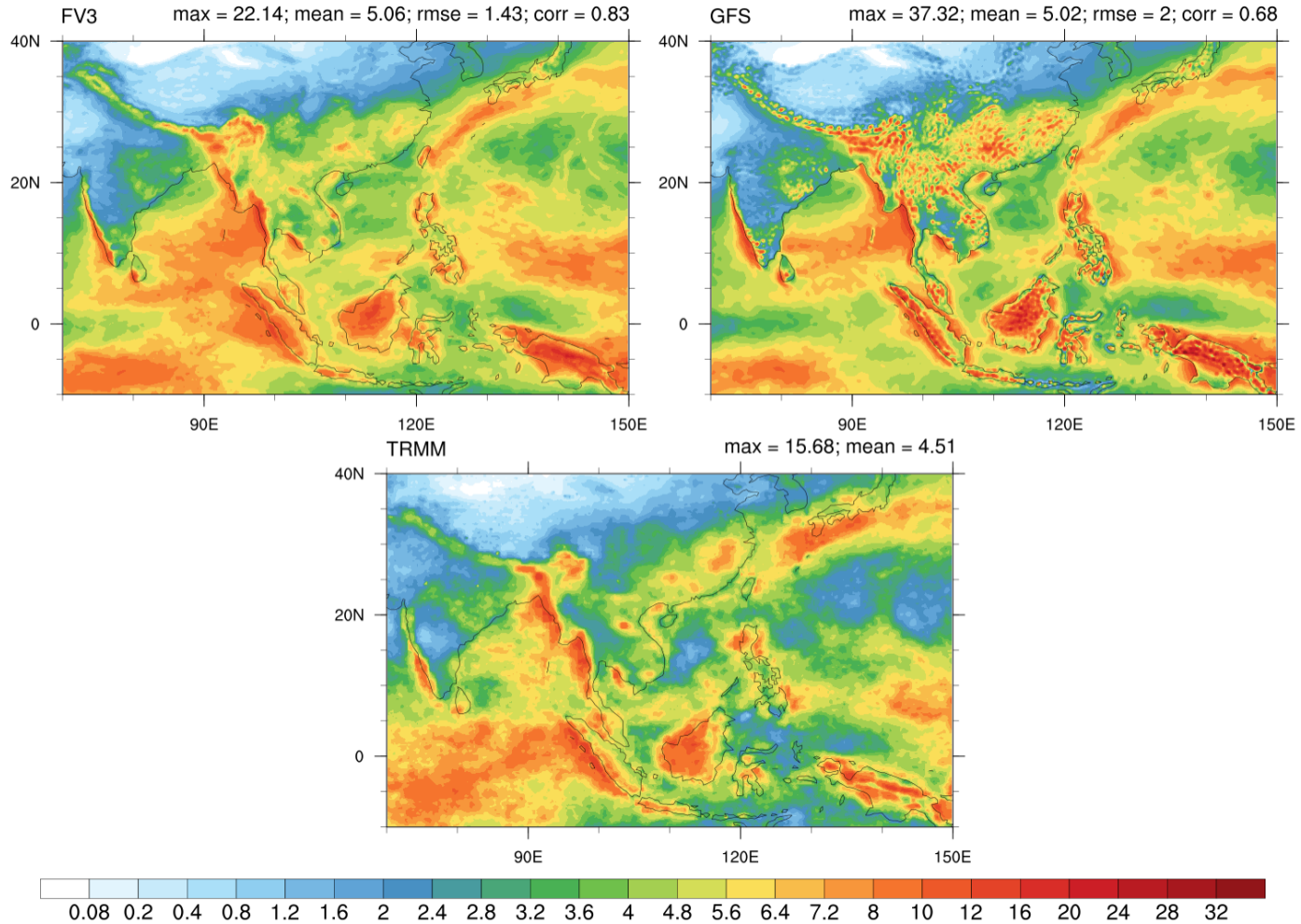
ANN Mean Precipitation Rate (mm/day)



Why spectral models are bad at high resolution?

South Asia

ANN Mean Precipitation Rate (mm/day)

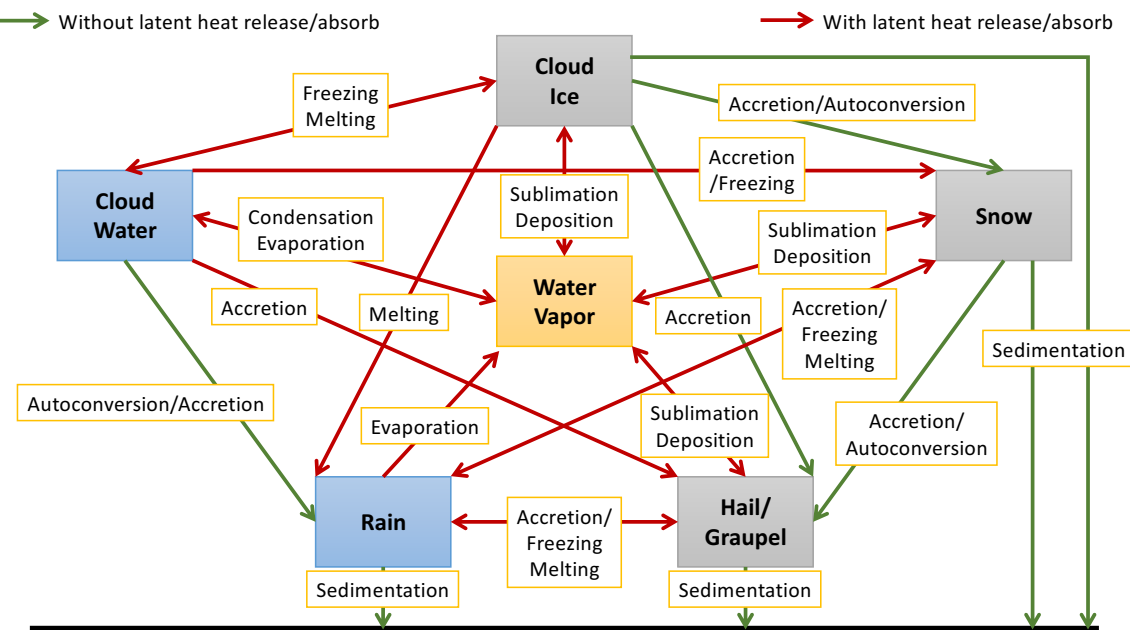


Making fvGFS suitable for all-scale predictions:

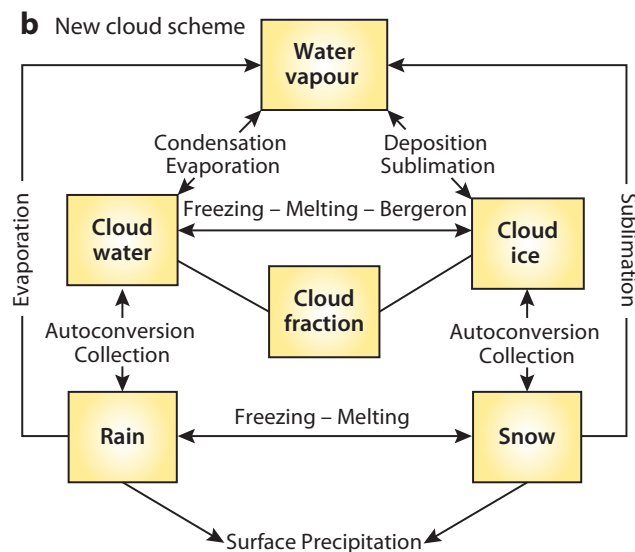
The 1st step: replacing the GFS's cloud Micro-Physics (MP) with **GFDL_MP**

- Designed for seasonal predictions (Chen & Lin 2011) and climate simulations, with “resolution-dependent” vertical & horizontal sub-grid distribution (based on FV concept)
- Tune for global balances, in particular, radiative balance at TOA
- Based on 1st principles: “*Ooyama-compliant*” and consistent with FV3 (heat & momentum transported by falling condensates)
- Computationally efficient time-implicit fall of precipitating condensates (rain, snow, graupel, and cloud ice)
- Compatible with cloud fields from latest IFS (4 condensates)

GFDL cloud microphysics (6 species)



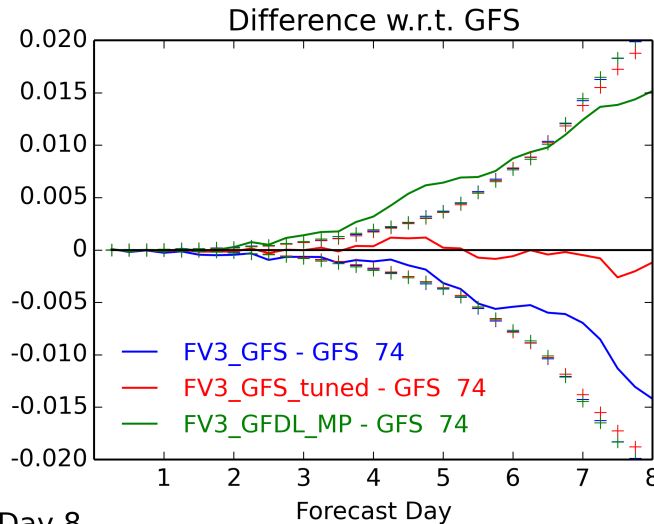
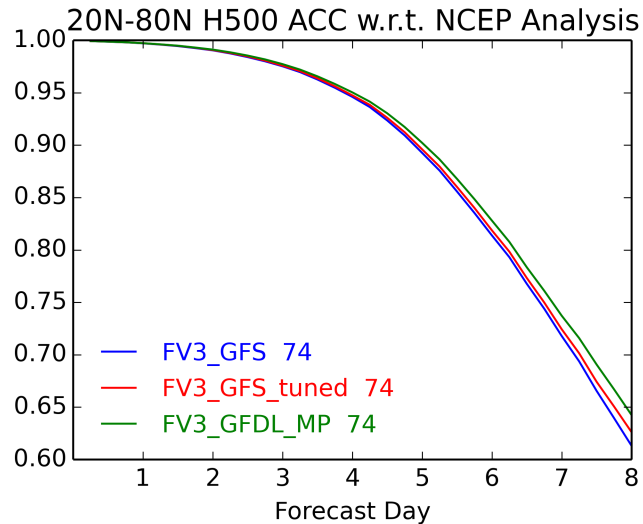
ECMWF cloud microphysics (5 species)



The 1st step towards regional-global unification:

Do no harm to global skill while enabling convection-scale with an advanced cloud microphysics

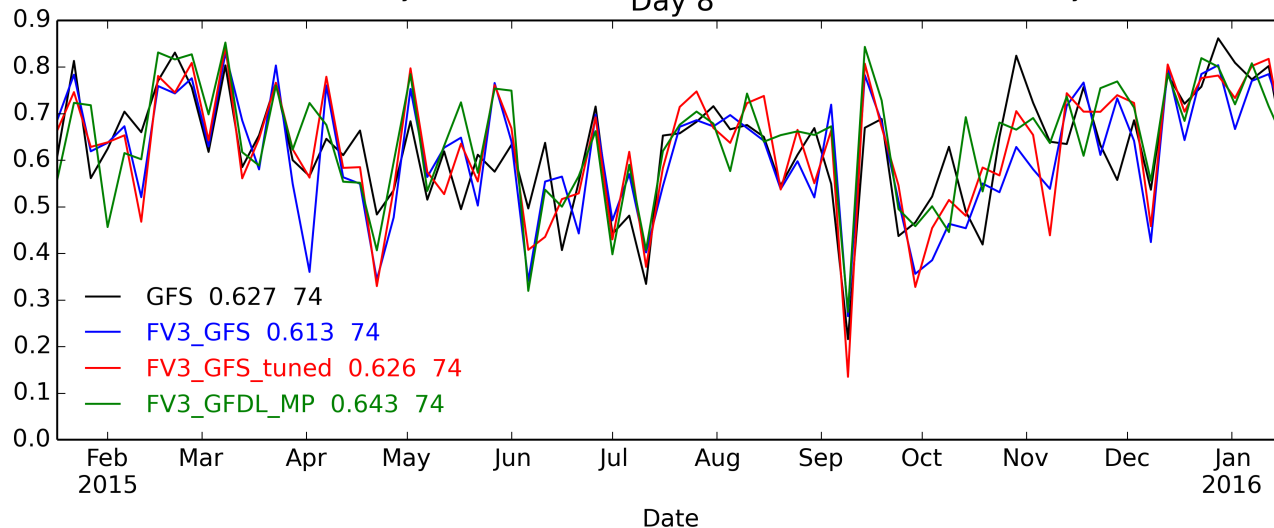
Relative Skill to Operational GFS



13-km fvGFS with GFDL_MP

13-km fvGFS with tuned GFS

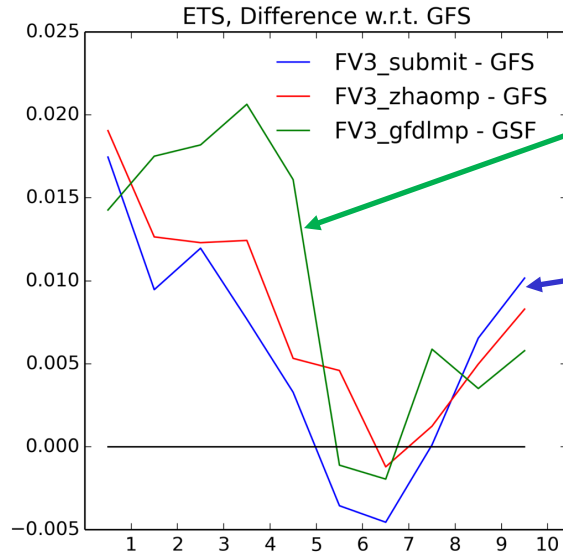
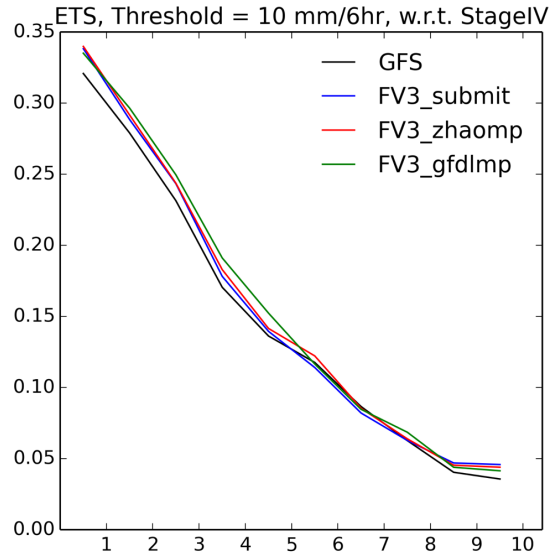
13-km fvGFS (no tuning)
(as submitted to NGGPS)



Equitable Threat Score over CONUS

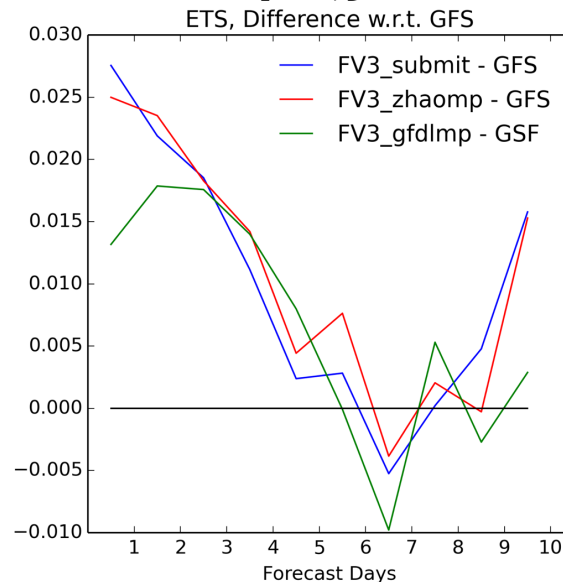
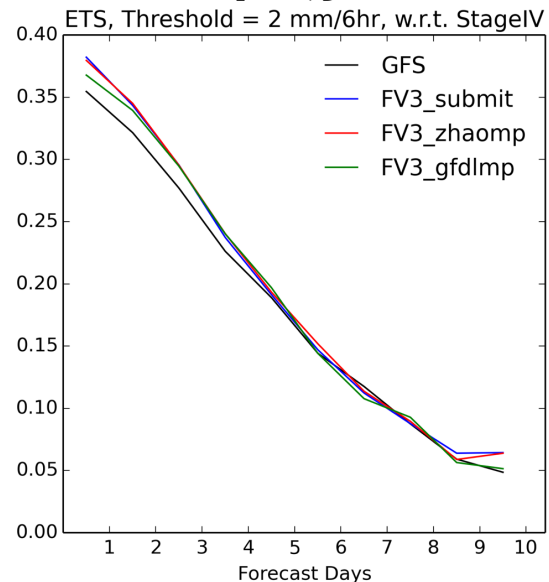
(based on NGGPS 74 cases)

GFDL_MP made a big improvement for strong & weak events



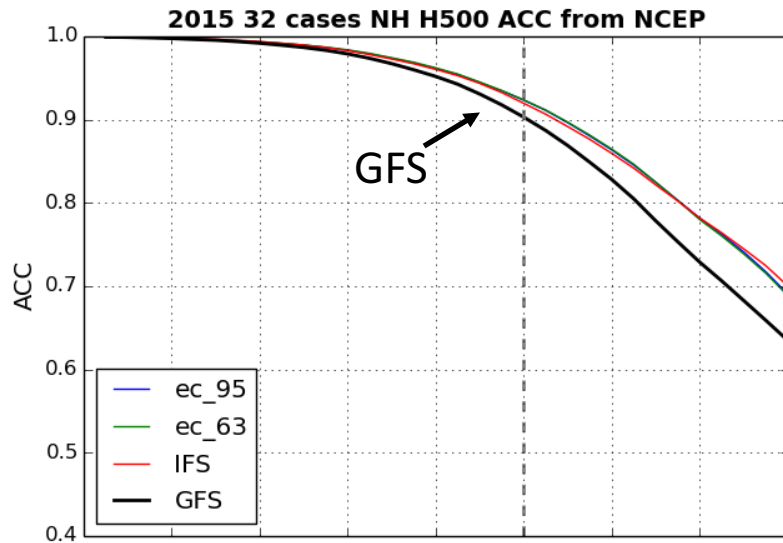
fvGFS with GFDL_MP

**13-km fvGFS
(submitted to NGGPS)**



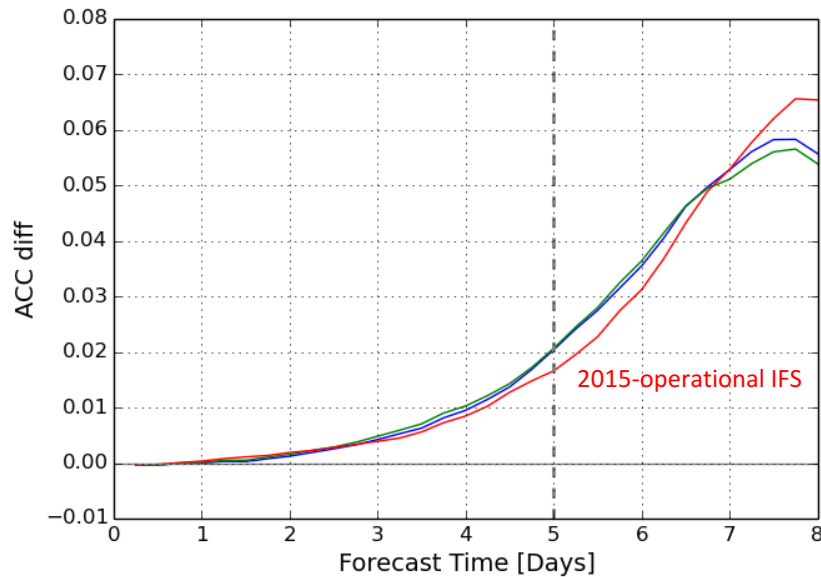
Transplant Experiments: 13-km fvGFS using IFS initial conditions (9-km, L137)

Period: 20150814–20160116 (32 cases)



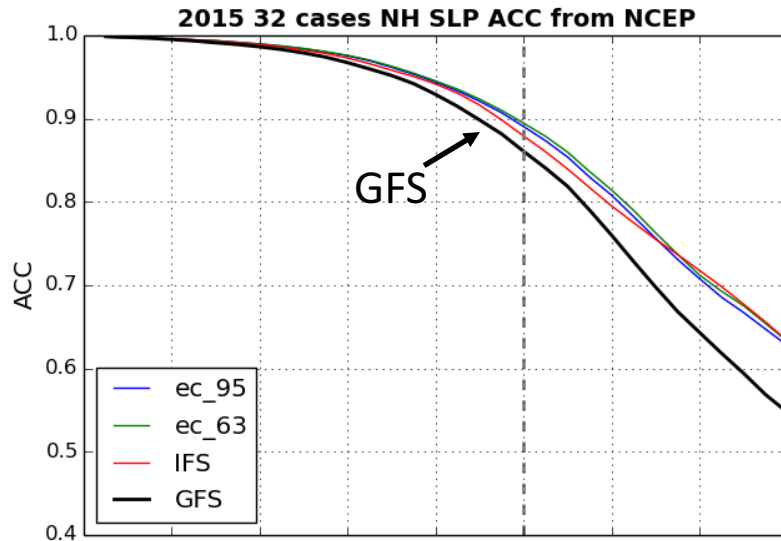
- Using ICs from ECMWF IFS, fvGFS with GFDL_MP outperforms the 2015-operational IFS (Red) and the GFS (black)
- Using ICs from GFS, it is extremely difficult to beat IFS
- Of course, H500 ACC is not the only metric

Skill (H500 ACC) relative to GFS



IFS ICs courtesy of
Linus Magnusson, ECMWF

Transplant Experiments (32 cases): Sea-Level Pressure (SLP)



- FV3 SLP ACC is relatively higher:
Spectral models (IFS and GFS) perform relatively worse in SLP than in H500
- For the 32 cases, even with various handicaps, fvGFS outperforms ECMWF-IFS with same IC from IFS

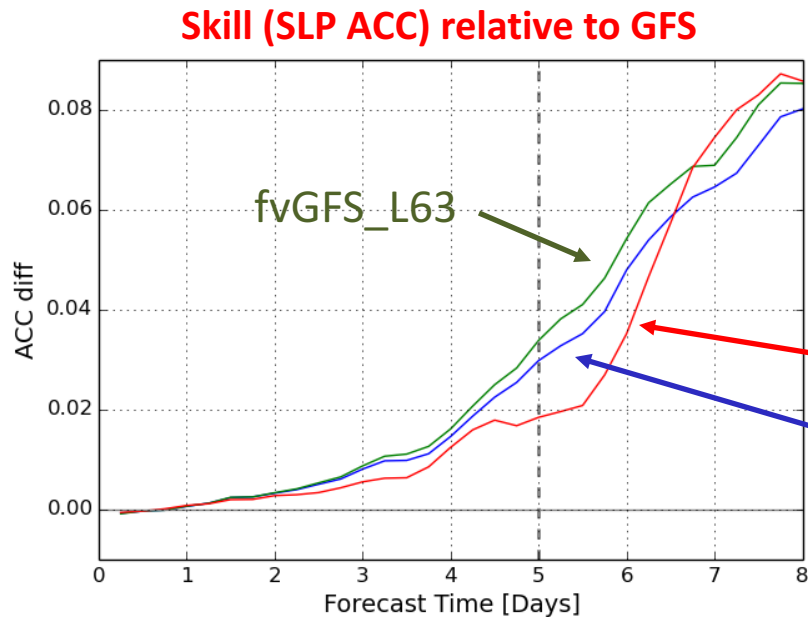
SLP ACC at Day-5

fvEC_63: 0.895

fvEC_95: 0.891

IFS: 0.879

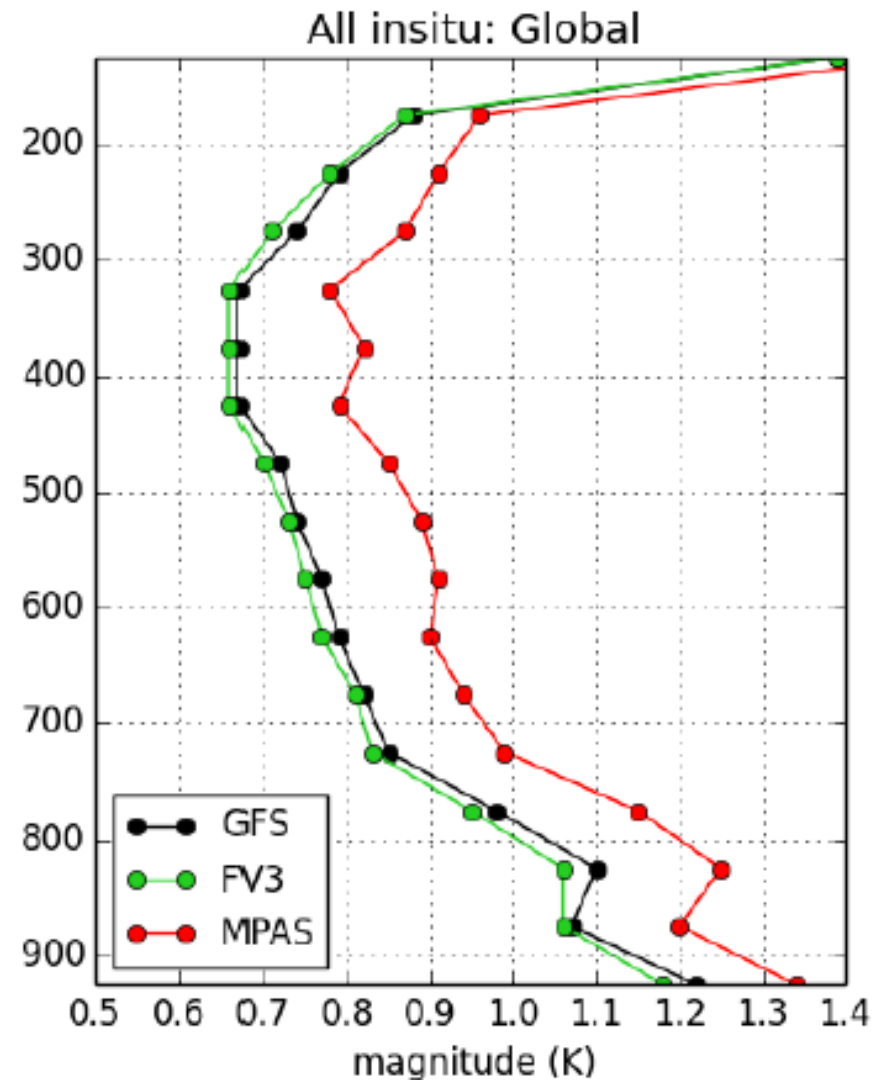
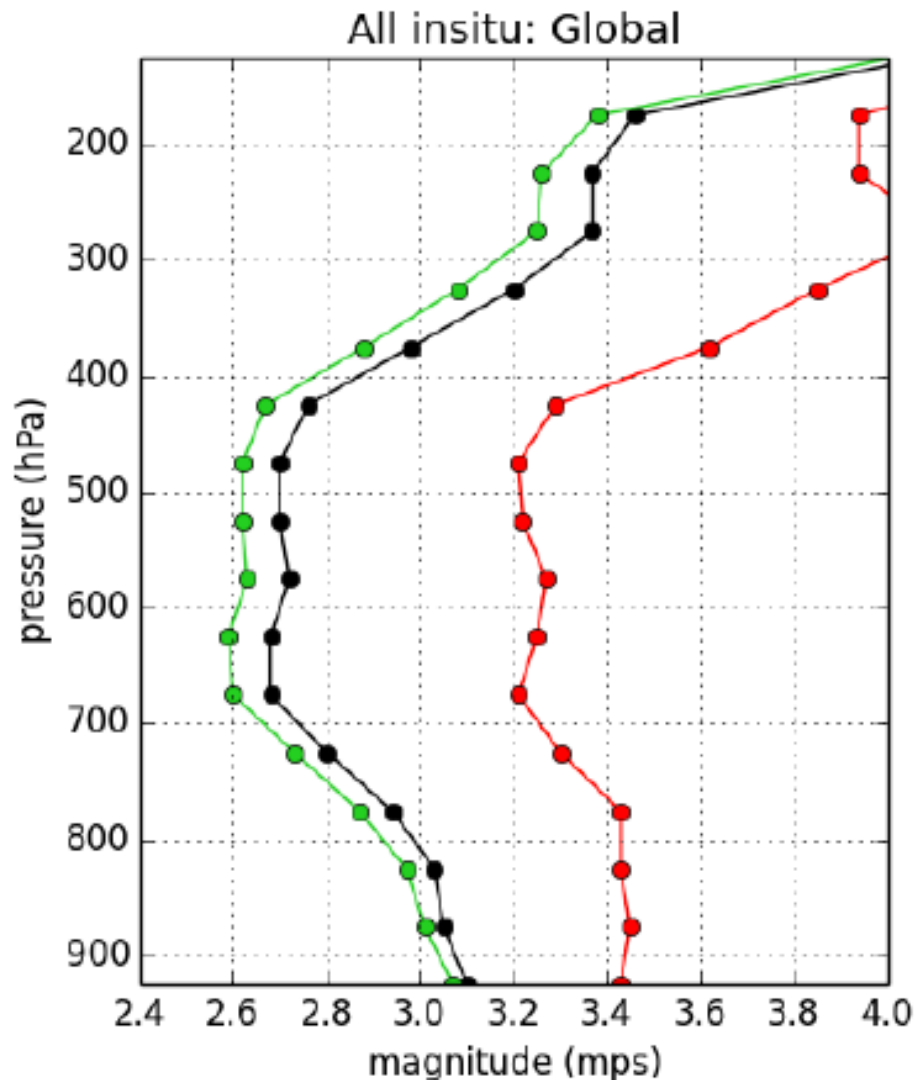
GFS: 0.861



IFS ICs courtesy of
Linus Magnusson, ECMWF

DA cycle with FV3 and MPAS: NGGPS phase-2 (J. Whitaker)

Vector Wind (left) and Temp (right) O-F (2015090500-2015092618)



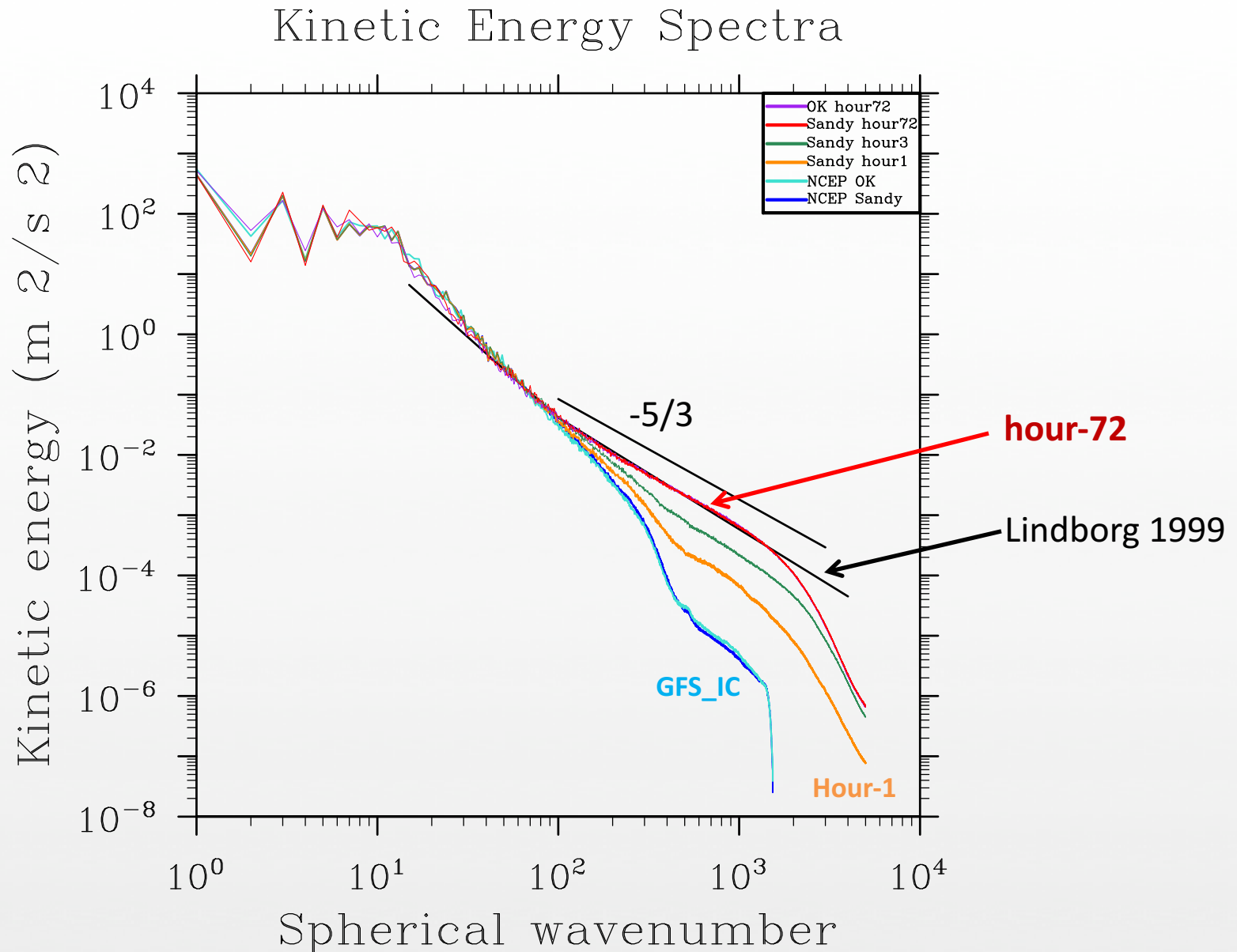
Final notes:

- The *hydrostatic* model for Numerical Weather Prediction is near the end of its useful life
 - It's time to go full non-hydrostatic for all NWP models
- R2O2R: Today's NWP model could be tomorrow's "high-resolution" climate model
- Goal for 2018-2019
 - Boldly step into the NWP gray-zone (~7.5 km) where non-hydro dynamics-microphysics interaction is increasingly more important
- To be "second to none" in NWP, the "rate of improvement" must be higher than the competition. A fast pace development cycle involving a small team of experts in "physics", "dynamics", and "DA" is desperately needed in the US
 - Must have overwhelming resources to win the (NWP) war – a Colin Powell doctrine

Supplemental Slides

KE spectrum from GFDL “Super HiRAM”

(FV3 with modified GFDL AM4 physics at globally uniform ~3.2 km)



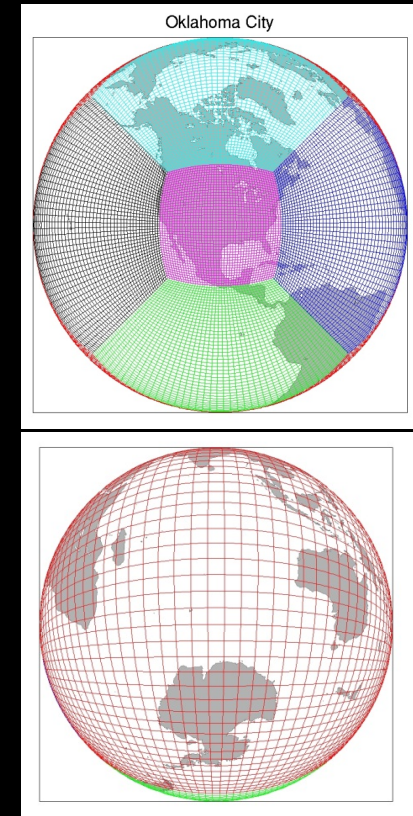
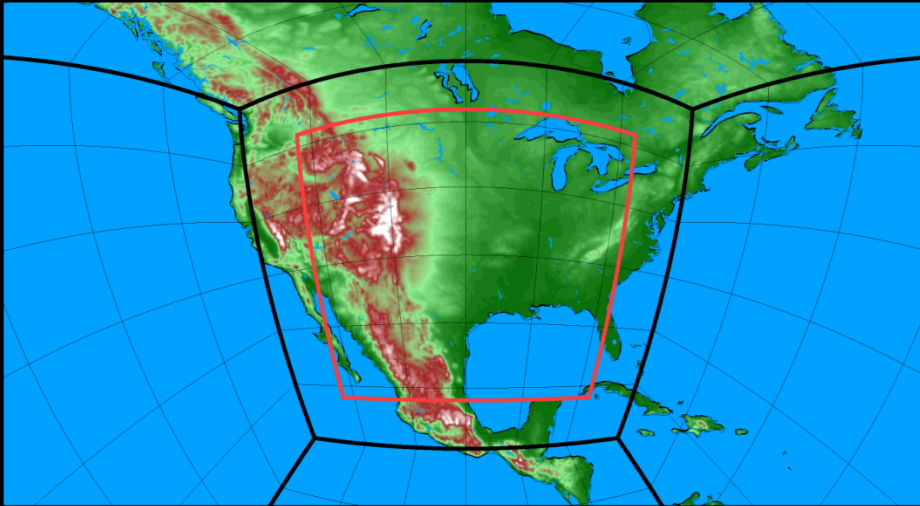
Achieving thunderstorm-resolving resolution “TODAY” in a unified meso-global prediction system

1) Grid stretching (smooth variation of grid spacing)

1) 2-way nesting (Harris and Lin 2014)

FV3 is uniquely suitable for 2-way nesting, due to the application of two-time-level Finite-Volume transport scheme

2) Optimal combination of the “stretching” and “nesting”

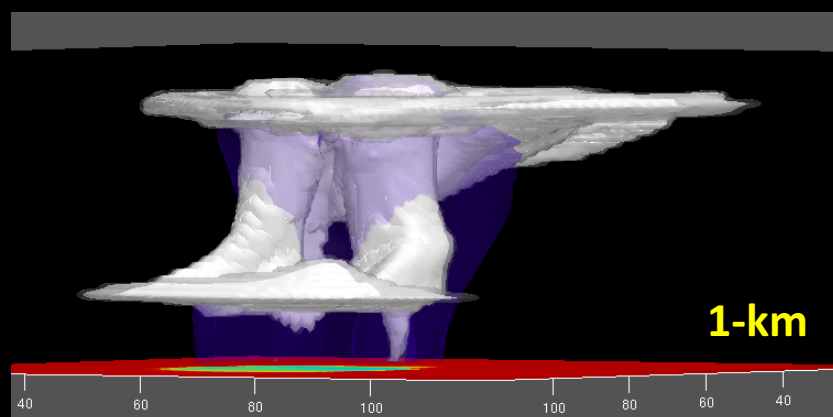
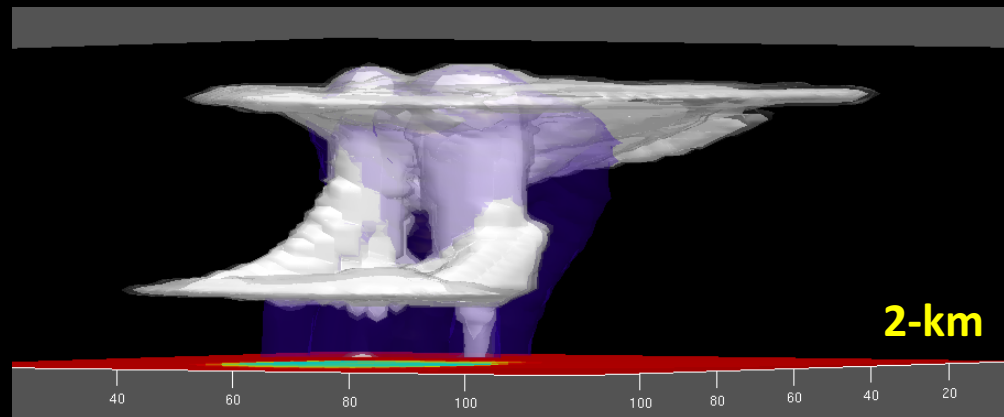
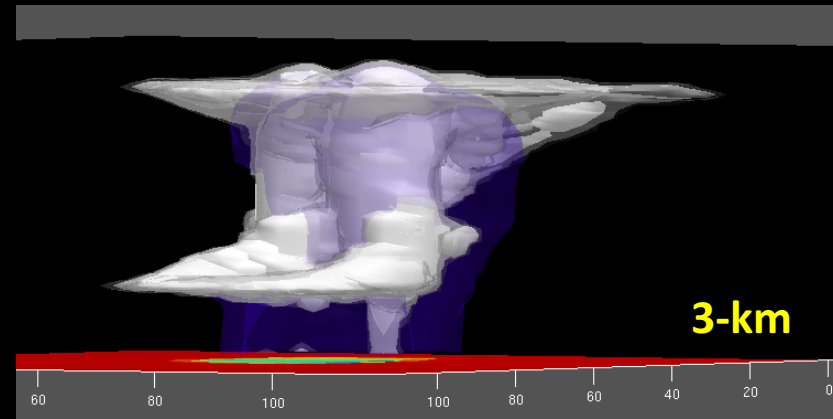
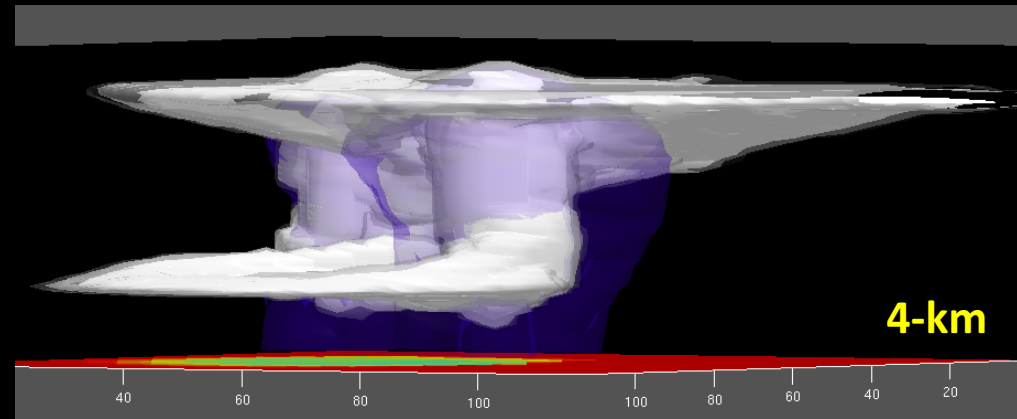


Example:

~ 3 km without the nest (black)

~ 1 km with a 2-way nest (red)

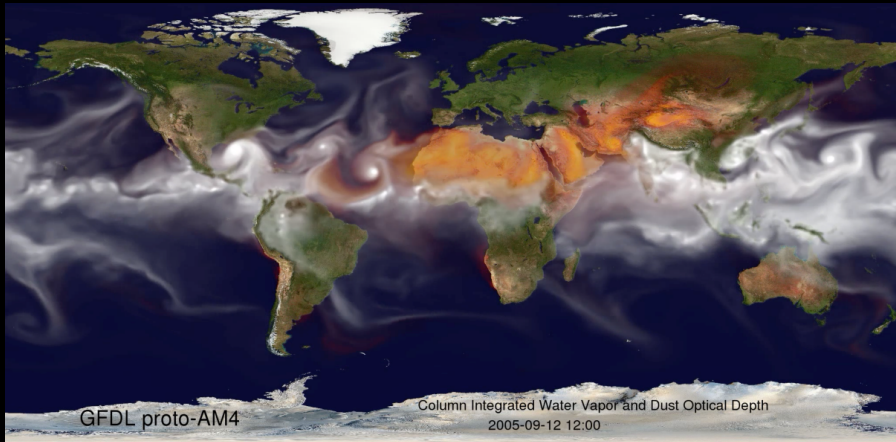
Simulations of tornado-producing super-cell storms with GFDL's variable-resolution FV³



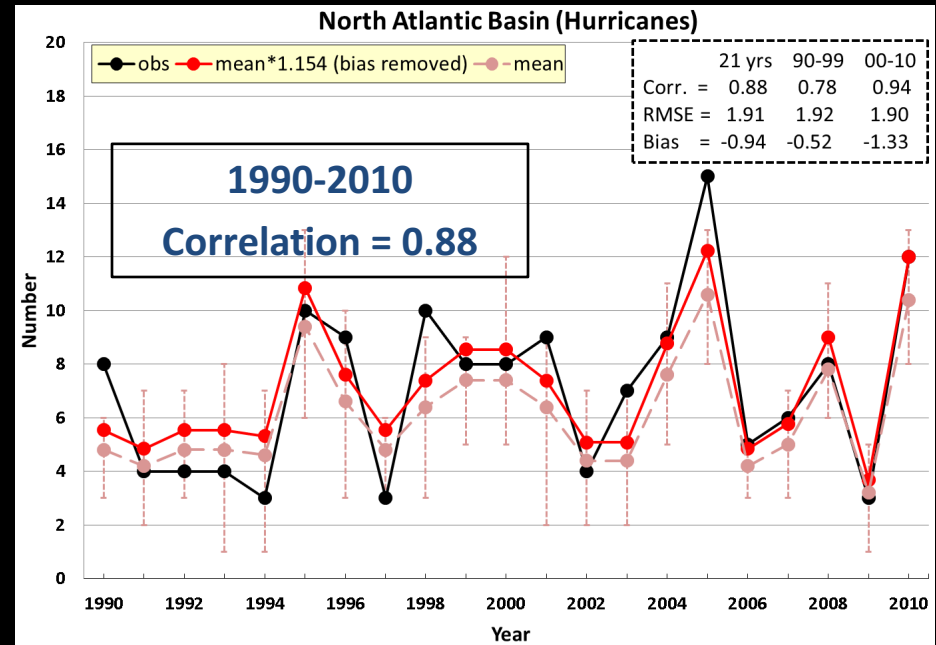
Lin and Harris (manuscript)

GFDL's research on Predictions for all-scale

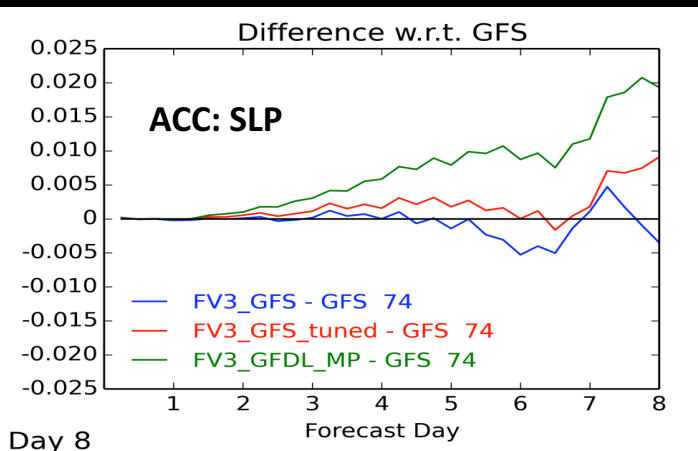
Dust (orange) and water vapor (white)
GFDL 50-km AM4 for IPCC



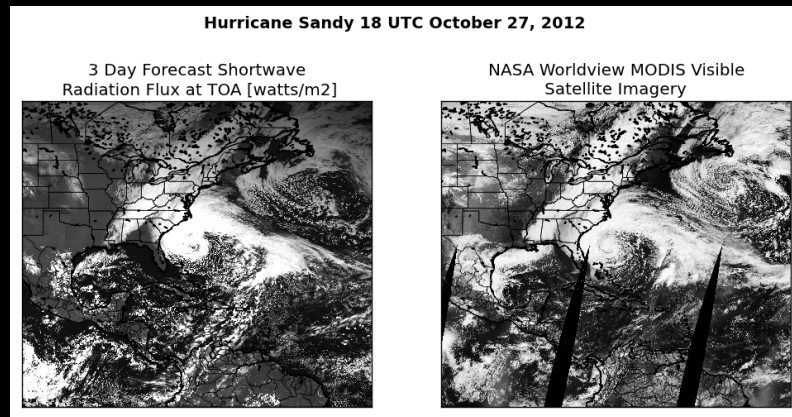
Seasonal Hurricane Prediction (25-km HiRAM)



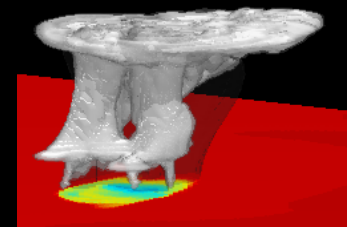
Medium-range NWP (13-km, phase-2 NGGPS)



Global cloud-permitting Predictions (3-km, phase-1 NGGPS)



Severe Storm prediction (1 km, Super HiRAM)



Central Africa

ANN Mean Precipitation Rate (mm/day)

